

# Early Super Soft Source spectra in RS Oph

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## Abstract

Recent Swift X-ray monitoring campaigns of novae have revealed extreme levels of variability during the early super-soft-source (SSS) phase. The first time this was observed was during the 2006 outburst of the recurrent nova RS Oph which was also extensively covered by grating observations with XMM-Newton and Chandra. I focus here on an XMM-Newton observation taken on day 26.1, just before Swift confirmed the start of the SSS phase, and a Chandra observation taken on day 39.7. The first observation probes the evolution of the shock emission produced by the collision of the nova ejecta with the stellar wind of the companion. The second observation contains bright SSS emission longwards of 15 Å while at short wavelengths, the shock component can be seen to have hardly changed. On top of the SSS continuum, additional emission lines are clearly seen, and I show that they are much stronger than those seen on day 26.1, indicating line pumping caused by the SSS emission. The lightcurve on day 39.7 is highly variable on short time scales while the long-term Swift light curve was still variable. In 2007, we have shown that brightness variations are followed by hardness variations, lagging behind 1000 seconds. I show now that the hardness variations are owed to variations in the depth of the neutral hydrogen column density of order 25%, particularly affecting the oxygen K-shell ionization edge at 0.5 keV.

**Keywords:** Cataclysmic variables - Recurrent novae - Spectroscopy - X-rays - individual: RS Oph.

## 1 Introduction

The 2006 outburst of the recurrent symbiotic nova RS Oph has attracted a large number of observers to study the outburst in unprecedented detail and many wavelength bands. In particular the coverage in X-rays has considerably improved since the previous outburst in 1985 by initiating the first high-density X-ray monitoring of a nova with the X-ray Telescope (XRT) on board Swift, starting on day 3.38 after initial explosion (Bode et al. 2006a). Early shock emission originated from kinetic energy from the nova ejecta that were dissipated in the slow, dense stellar wind of the giant companion. The expected X-ray spectrum is that of a collisional plasma which was confirmed by spectral models to the low-resolution EXOSAT spectra taken in 1985 (figure 3 in O'Brien et al. 1992) and the Swift/XRT spectra (Bode et al. 2006b). The X-ray grating spectrometers on board XMM-Newton (Reflection Grating Spectrometer RGS) and Chandra (Low- and High Energy Transmission Grating Spectrometers LETGS and HETGS) allow spectral lines to be resolved, and in simultaneous RGS/HETGS spectra taken on day 13.8 after the initial explosion (2006 February 12.83), bremsstrahlung continuum, H-like and He-like emission lines, and numerous Fe lines could be identified. A detailed analysis exploring the information from the emission lines yielded the distribution of electron temperatures and abundances (Ness et al. 2009).

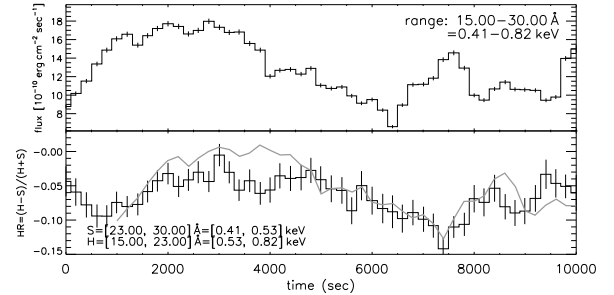


Figure 1: Reproduction of figure 8 from Ness et al. (2007). The Chandra light curve on day 39.7, taken during the early high-amplitude variability phase, was also highly variable on shorter time scales. The hardness ratio, shown in the bottom, evolved with the same variability patterns but lagged 1000 seconds behind the brightness variations. Reproduced by permission of the AAS.

Further grating observations were taken, e.g., on days 26.1, 39.7, 54.0, 66.9, and 111.7 that were guided by continued dense Swift monitoring (see table 1 in Ness et al. 2009 and top of figure 2 in Osborne et al. 2011). During the XMM-Newton observation on day 26.1, a jump in count rate was discovered by Nelson et al. (2008) that was exclusively attributed to additional soft emission, possibly indicating the start of the SSS phase. The bremsstrahlung con-

tinuum has faded and become softer, and also the ratios of H-like to He-like emission line strengths have shifted in favor of the He-like lines, indicating a cooling trend in the shocked plasma (Ness et al. 2009). The Swift observations of the  $\sim 60$  day SSS phase are described in Osborne et al. (2011). Between days  $\sim 30$  and 45, the X-ray count rate was highly variable between  $\sim 10$  counts per second (cps) and 200 cps, and then stabilized at  $\sim 300$  cps (figure 2 in Osborne et al. 2011). This was a new discovery and was later also observed in other novae and might be a general phenomenon. During this high-amplitude phase, a Chandra observation was taken on day 39.7, without yet knowing about the risks of observing during times of fainter emission. While this was the case, the soft emission was still bright enough for a well-exposed grating spectrum that was first presented by Ness et al. (2007). The blackbody-like continuum contained deep absorption lines from highly ionized species such as O VIII and N VII that were blue shifted by  $\sim 1200 \text{ km s}^{-1}$ . The line profiles contained clear signs of emission lines in the red wings (figure 5 of Ness et al. 2007) which could either come from residual shock emission or are part of P Cyg profiles. During this observation, the nova was also highly variably on shorter time scales, and Ness et al. (2007) reported that the hardness variations followed the same up- and down trends but lagged 1000 seconds behind (see Fig. 1).

I focus here on two new aspects:

- 1) The emission line components on top of the SSS continuum (shown in figure 5 of Ness et al. 2007), compared to the same lines before the SSS phase started, are much stronger than expected from a cooling plasma (Sect. 2.1).
- 2) Closer inspection of the brightness/hardness changes during the day 39.7 observation show that the hardness changes are due to changes in the depth of the O I absorption edge. Modeling shows that the overall column density increases with decreasing brightness (Sect. 2.2).

## 2 Observations and Analysis

A full log of all XMM-Newton and Chandra grating observation that were taken of the 2006 outburst of RS Oph is given in table 1 in Ness et al. (2009) out of which I focus on the ones taken with XMM-Newton between 2006 March 10, 23:04 and March 11, 02:21 (ObsID 0410180201) and with Chandra 2006 March 24, 12:25 - 15:38 (ObsID 7296). The calibrated spectra are shown in direct comparison in Fig. 2 using the same flux units without rescaling.

### 2.1 Contributions of shock emission to SSS continuum spectrum

In the top panel of Fig 2, the full spectra are shown in logarithmic units to overcome the great contrast in brightness between the two observations. At wavelengths  $\lesssim 15 \text{ \AA}$ , the two spectra are similar in nature, mainly differing in the brightness of the continuum. The weaker continuum on day 39.7 can be explained by the continuation of the fading trend of the shocks that has already been established from the observations between days 13.8 and 26.1. The strengths of the emission lines have hardly changed. At wavelengths  $\gtrsim 15 \text{ \AA}$ , the emission lines seen on day 26.1 were outshone by the bright continuum on day 39.7, and it is not intuitively clear how they have evolved. In the panels below, four lines are shown in more detail in linear units. The open histograms in the panels below represent the day 39.7 spectrum while the colored shades are the day 26.1 spectrum, added to the median flux of the day 39.7 spectrum, taken over the narrow wavelength range selected for each panel. The Mg XII/XI lines have faded from day 26.1 and the Ne X line at  $12.1 \text{ \AA}$  is about equally strong at both times while these lines have become somewhat narrower. The panels further below show that the lines on top of the SSS continuum have become stronger from day 26.1 to 39.7, depending on the strength of the continuum. The Fe XVII line at  $15 \text{ \AA}$ , in the Wien tail of the SSS continuum, is only slightly stronger while the O VIII and N VII lines, near the peak of the SSS continuum, are much stronger, defying the general trend of fading emission from the shocks. A similar result has been found by Schönrich & Ness (2008) who show in their figure 1 the evolution of the volume emission measure for various emission lines as a function of their peak formation temperature assuming collisional equilibrium. The line fluxes of O VII and O VIII from the observation taken on day 39.7 yield clearly discrepant values, orders of magnitude brighter than in observations without SSS emission, while those emission lines that arise at shorter wavelengths are consistent with the other observations.

### 2.2 Spectral changes with variability during early SSS phase

The high-amplitude variations during the early SSS phase are still not understood, leaving all options open such as changes in absorption, in intrinsic brightness, temperature, or in the rate of mass loss. A first approach to narrow down the options, I present the spectra and how they changed with variability. During the early variability phase of RS Oph, a short Chandra observation taken (day 39.7), and

the spectral evolution is illustrated in Fig. 3. The light curve, already shown in Fig. 1, is shown in the right, turned around by 90° clockwise to follow the vertical time axis in downward direction. The blue dotted line is the hardness light curve from the bottom panel of Fig. 1 that was rescaled to fit in the same graph. Along the same vertical time axis, a series of adjacent LETGS spectra are shown in the central panel with wavelength along the horizontal axis and flux encoded in a color scheme, where increasing flux is represented by colors light green, yellow, orange, red, dark blue to light blue. In the top panel, two spectra are shown that have been integrated over the time intervals marked with horizontal dashed lines in the central panel shaded areas in the right panel. The colors of the dashed lines and shades correspond to the plot style of the spectra in the top, thus light blue and orange shadings in the right correspond to the light blue shade and orange thick line in the top, respectively. The two spectra have been normalized to coincide in the wavelength range 15 – 22 Å.

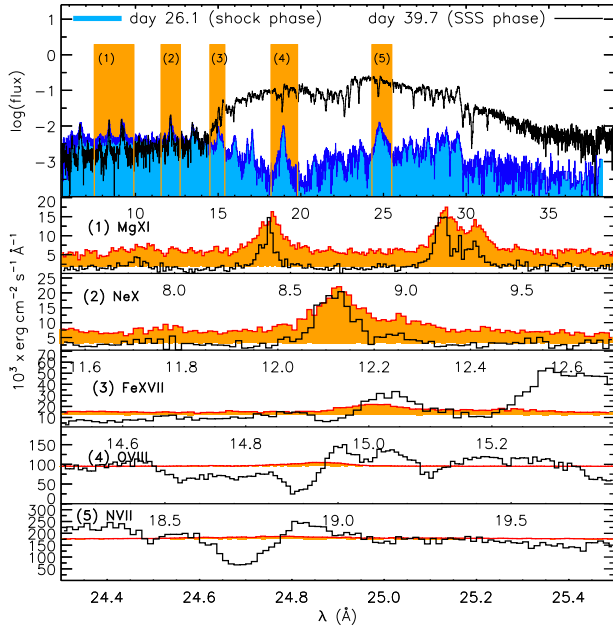


Figure 2: Comparison of a pre-SSS spectrum of RS Oph taken on day 26.1 and an SSS spectrum taken on day 39.7. In the top panel the entire wavelength range is shown in logarithmic units, illustrating that at short wavelengths, below  $\sim 15$  Å, the spectra are similar, only showing a decline the Bremsstrahlung continuum component from day 26.1 to day 39.5. In the panels below, narrow wavelength regions are shown where the pre-SSS spectrum is added to the median of the day 39.7 spectrum in the same flux units. While short-wavelength lines have hardly changed, the excess emission lines on top of the SSS continuum are much stronger than before the start of the SSS phase.

Ness et al. (2007) had extracted spectra from time intervals of bright and faint episodes, roughly corresponding to the time intervals 0.3 – 1.0 hours of elapsed time (bright) and 1.1 – 2 hours, respectively, and found differences in the spectral shape. I have now chosen time intervals that are shifted by 1000 sec in order to probe the hardness light curve rather than the intensity light curve. The two normalized spectra in the top clearly show that the variability in hardness is purely owed to changes in the depth of the O I edge at 22.8 Å, yielding the steeper edge 1000 sec after a low-flux episode. Ness et al. (2007) had found changes in O I on longer time scales between the grating observations taken on days 39.7, 54.1, and 66.9 and explained these by changes in the degree of ionization of oxygen. Only neutral oxygen produces the deep edge at 22.8 Å while ionized oxygen is more transparent to X-rays, leading to a flatter edge. The intense soft continuum X-ray source can ionize the neutral elements in the surroundings and thus make them more transparent. On the other hand, if the continuum source fades, the surrounding material recombines, leading to an increase in the O I edge.

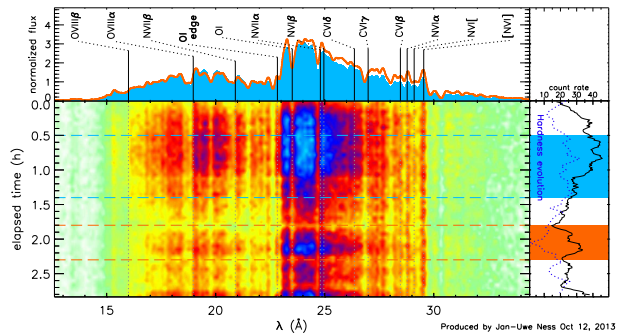


Figure 3: Dynamic spectrum for the Chandra observation of RS Oph taken on day 39.7 after the 2006 outburst. The zero-th order light curve is shown to the right with three colored shades marking time intervals from which the spectra in the top have been extracted. Line labels that belong to strong transitions are included. The central image is a brightness spectral/time map that uses a color code from light green to light blue representing increasing flux values.

The changes in the depth of the O I absorption edge could be caused by changes in the degree of ionization of circumstellar oxygen. Ness et al. (2007) argued that the observed time lag of 1000 seconds is consistent with the time scale for ionization/recombination in a plasma with density  $\sim 10^{11} \text{ cm}^{-3}$ . Since all circumstellar material would experience the same changes in their degree of ionization, this would lead to an overall change in  $N_H$ . Another possibility is a non-uniform radial distribution of the oxygen abundance within the ejecta that

could be caused by beta decay of oxygen isotopes produced during CNO burning. If during times of brighter and fainter emission, different regions of the photosphere are visible, the difference in the oxygen abundance would only affect the depth of the O I absorption edge.

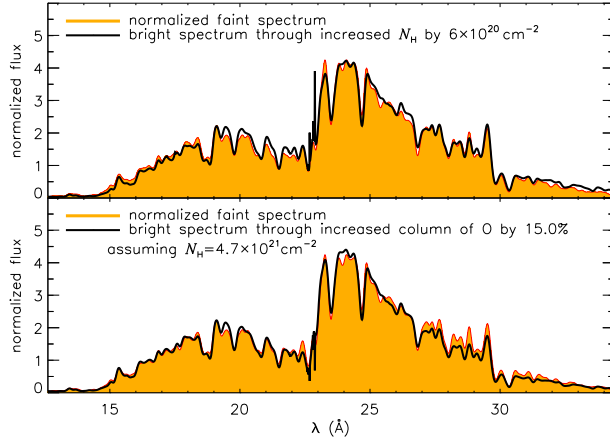


Figure 4: Testing two hypotheses to explain the spectral changes between hard/bright (blue shades in top panel of Fig. 3) and soft/faint (orange thick line in Fig. 3) spectra by the black thin lines. The normalized soft/faint spectrum is shown as orange shadings while the black line corresponds to two types of modifications of the bright/faint spectrum, also normalized (see text). **Top:** Overall increase of  $N_H$  by 26% of  $N_{H,CS}$ . **Bottom:** Increase only of O I column by changes in O abundance of 15%.

In Fig. 4, I test these two scenarios in the top and bottom panels, respectively. Shown is the normalized faint/soft spectrum in orange shadings (orange line in the top panel of Fig. 3) while the black curve represents a modification of the brighter/harder spectrum, trying to reproduce the faint/soft spectrum. In the top panel of Fig. 4, the black curve was computed by dividing the bright/hard spectrum itself by the transmission coefficients calculated from the warm absorption model developed by Wilms et al. (2000), and then normalized. The faint/soft spectrum is qualitatively well reproduced assuming a value of  $N_H = 6 \times 10^{20} \text{ cm}^{-2}$ , indicating that the change in hardness can be explained by an increase of  $N_H$  by this amount. The full amount of the hydrogen column was found by Ness et al. (2007) as  $N_H = N_{H,ISM} + N_{H,CS} = 4.7 \times 10^{21} \text{ cm}^{-2}$ , consisting of the well-known interstellar component  $N_{H,ISM} = 2.4 \times 10^{21} \text{ cm}^{-2}$  and an additional circumstellar component  $N_{H,CS}$ . An increase by  $6 \times 10^{20} \text{ cm}^{-2}$  thus corresponds to  $\sim 26\%$  of  $N_{H,CS}$ .

In the bottom panel of Fig. 4, the black curve was computed by first dividing the bright-hard spectrum by the transmission coefficients of an absorber

with  $N_H = 4.7 \times 10^{21} \text{ cm}^{-2}$ , assuming cosmic abundances and then multiplying by the coefficients resulting from the same absorption model assuming a modified oxygen abundance. The faint/soft spectrum is well reproduced up to  $\sim 27 \text{ Å}$ , but the black curve drops well below the faint/soft spectrum at longer wavelengths. The better agreement between the black line and the faint/soft spectrum in the upper panel demonstrates that an overall increase of  $N_H$  has occurred rather than a change in the oxygen abundance alone.

### 3 Summary and Conclusions

A comparison of grating X-ray spectra before and after the start of the SSS phase shows that the emission lines that were seen on top of the SSS continuum are not simply a continuation of the early shock emission. Only emission lines that arise at wavelengths where strong continuum emission is present are amplified compared to the pre-SSS level, strongly suggesting photoexcitation effects. The line profiles in the early SSS spectrum of RS Oph can thus be understood as P Cyg profiles.

The early high-amplitude variability in RS Oph and other novae still awaits an explanation. The Chandra observation during a minimum of these variations revealed that variability also occurs on shorter time scales. The comparisons in this article show that the hardness changes following brightness changes are consistent with variations in  $N_H$  of  $\sim 26\%$  which can be explained by variations in the overall degree of ionization caused by the changes in intensity and thus variations in the effectiveness of photoionization.

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